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THE INFINITE PARALLEL-WIRE ARRAY OVER A GROUND PLANE: A CODE FO--ETC(U)
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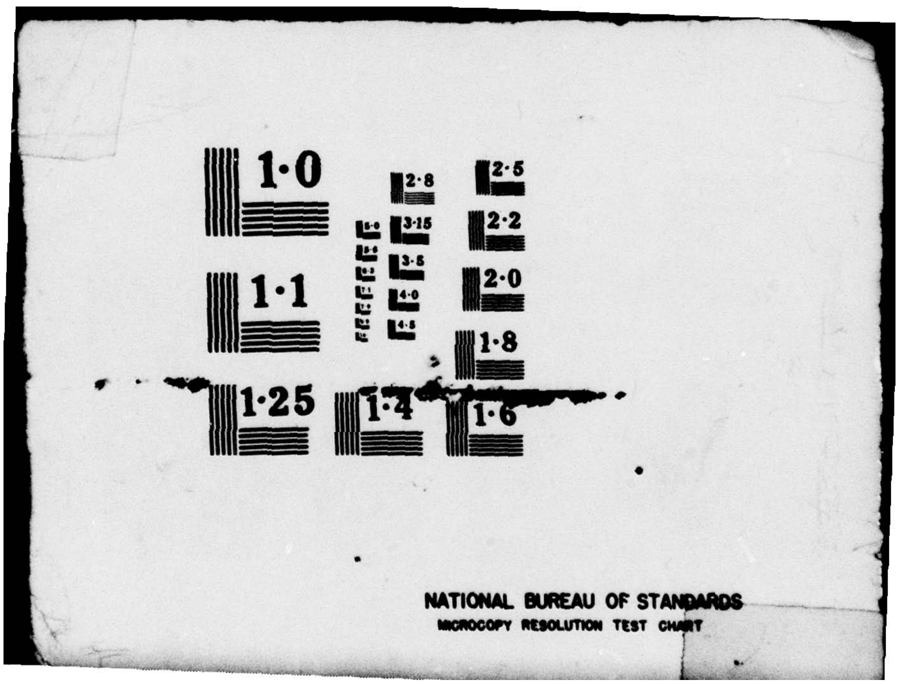
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Elements of the multiwire parallel array over a ground plane are addressed with a systems-related EMP vulnerability assessment and hardening orientation. An abbreviated computer program supported by experimental data permits a calculation of the degree of interaction of the wires of a parallel array, the individual wire and array impedance to ground, and the relative current distribution among the wires exclusive of wire end loading. This represents the foundation for an inclusive EMP code.

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CONTENTS

FIGURES

1. INTRODUCTION

This is the third in a series of reports treating the multiwire array and designed to meet the needs of an EMP vulnerability assessment and hardening program.[1,2] The approach to the shielded multiwire cable is extended to the wire array over a ground plane. A limited code is presented that calculates the wire current distribution, degree of wire coupling, and the effective single conductor equivalent for an array exclusive of end loading effects. Theory is compared with experiment for the case of wire arrays near a less than ideal ground plane.

2. THEORY

For a parallel-wire array over a lossless ground plane (and this treatment disregards wire end loading), the potential at any wire can be written in the form

$$V_N(x,t) = \sum_M Z_{NM} I_M(x,t); \; M = 1, 2, \ldots M' \quad , \tag{1}$$

where $I_M(x,t)$ is the current on wire M and M' is the total wire count. With the ground surface forming the image plane, Z_{NM} is (in mks units)[1]

$$Z_{NM} = \left(1/2\pi\varepsilon^{1/2}\varepsilon_0 C\right) \ln \left(r'_{NM}/r_{NM}\right) \quad , \tag{2}$$

where

r'_{NM} = distance between Nth conductor and image of Mth conductor,

r_{NM} = distance between Nth and Mth conductor

---

[1] *Michael J. Vrabel, The Multiwire Shielded Array—Theory and Code, Harry Diamond Laboratories, HDL-TR-1873 (October 1978).*

[2] *Michael J. Vrabel, User's Manual for SCWAR—A Multiwire Shielded Cable Code for a Systems Oriented EMP Vulnerability Assessment Program, Harry Diamond Laboratories, HDL-TR-1887 (May 1979).*

(for $N = M$, r_{NM} = radius of conductor N),

C = velocity of light in a vacuum,

ε_0 = 8.85×10^{-12} $C^2/n\text{-}m^2$, and

ε = relative dielectric constant.

This treatment is restricted to the case of a uniform dielectric constant for the medium above the ground plane.

The potential at a wire over a ground plane is of the form

$$V_N(x,t) = K(x,t)h_N \quad , \tag{3}$$

where

K = a coupling term whose exact form is unimportant to this treatment, and

h_N = the height of wire N above the ground plane.

Equations (1), (2), and (3) define a set of M' simultaneous equations that can be solved for the relative current on all array wires.

The impedance to ground of a single wire of the array is given by

$$z_N = \left[1/I_N(x,t)\right] \sum_M Z_{NM} I_M(x,t) \quad . \tag{4}$$

The effective impedance of the wire array to ground, z_W, is given by

$$1/z_W = \sum_M 1/z_M \quad . \tag{5}$$

From equation (5), the wire array can be cast in terms of an equivalent single conductor. The current response of the equivalent single conductor terminated into its characteristic impedance can be calculated using any single-wire EMP coupling code. If the effective single-wire response is known, the response of the individual array wires with end loading and loss terms included can be calculated by the same approach as applied to the multiwire shielded cable.

When the array is over an earth ground plane, two significant difficulties arise:

1. The concept of transmission-line termination for a very lossy system is ill-defined. Since the development of a wire-array code along the line indicated requires a calculation of an effective single-wire response with no reflection off the terminations, error is introduced with this calculation.

2. In general, the losses associated with an earth ground plane play a dominant role in establishing the late-time response of the array. Since a time domain code can handle such losses only approximately, the array late-time response will be distorted.

Within the context of developing an EMP systems-related code, the present approach can be justified on several grounds.

1. It permits the development of a reasonable code to handle a potentially very complex subject.

2. The uncertainties introduced by the late-time response are dominated by those resulting from other aspects of a vulnerability assessment program.

3. The early-time response, the region of most interest, is unaffected by loss term uncertainties introduced with this approach but rather reflects the accuracy (or lack thereof) of the single-wire code.

This treatment assumes that the cross-section dimensions of the array are fixed and that equilibrium conditions exist for all wires. The proper measure of the latter assumption is not the rise time of the incident signal but rather the wire responses as measured at either end or, because all coupling relates to the response of an equivalent single wire, the response of the equivalent conductor.

3. A COMPARISON OF THEORY WITH EXPERIMENT

Experiments were designed to test the predictions of section 2. The experiments were performed at the Harry Diamond Laboratories scale model facility employing a lossy ground plane composed of sand treated with a solution of sodium and calcium chloride. Soil resistivity measurements were not available. The effect of the poor ground conductivity is demonstrated in figure 1, which shows the experimental and theoretical response of a single wire as a function of height over a ground plane, all data normalized to the maximum height of measurement. For this and all subsequent measurements, the signal source is a horizontal dipole near the ground plane (angle of illumination 10 to 20 deg) at a range of

approximately 2 m. The measured response is the coupled early-time peak current due to a broadside illumination with a 5-ns square pulse. The rise time of the illuminating signal was such that equilibrium conditions were maintained across the wire array.

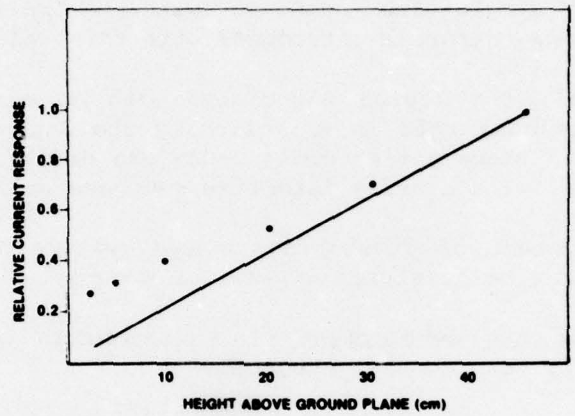

Figure 1. Comparison of theoretical single-wire current response (solid curve) over an ideal ground plane and response of a single wire over treated sand ground plane (both curves normalized to the 45.7-cm height).

Figure 2 shows the results of a series of two-wire measurements. The plotted data represent the ratio of the peak response of a single wire to the response of the same wire in the presence of a second wire. The abscissa is the distance between the two wires. For all points, the measuring wire was unmoved and the second wire was varied in a vertical plane both above and below the measuring wire and in a horizontal plane both in front of the measuring wire (that is, between the measuring wire and the dipole antenna) and behind it. The measuring wire was fixed 10.2 cm above the ground--a region, as shown in figure 1, where the effect of finite soil conductivity is becoming significant.

A series of three-wire measurements was performed. The geometry employed and the response data are given in figure 3. The response was measured as with figure 2, but with two rather than one additional wire. The open circle indicates the wire upon which all measurements were performed.

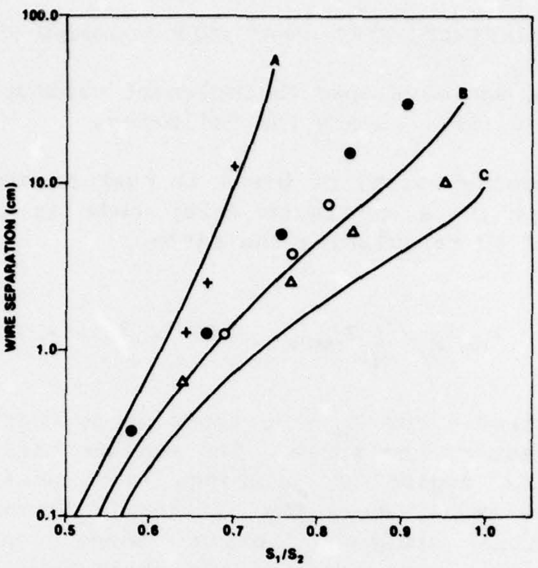

Figure 2. Ratio of current response (S_1) of single wire in two-wire array to current response (S_2) of single isolated wire (measuring wire fixed at 10.2 cm above ground plane). Curve A (theoretical) and points + (experimental)--second array wire varied in a vertical plane above measuring wire. Curve B (theoretical) and points o and ● (experimental)--second array wire varied in a horizontal plane in front (●) of measuring wire and behind (o). Curve C (theoretical) and points Δ (experimental)--second array wire varied in a vertical plane below measuring wire.

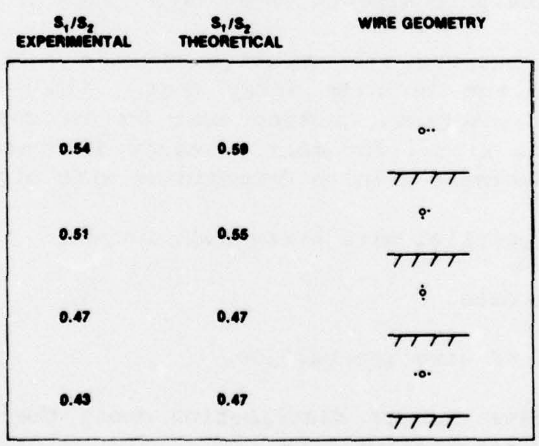

Figure 3. Experimental and theoretical current response of a three-wire array. S_1: response of a single wire in the array; S_2: response of same wire with remaining two removed. Drawings are scaled representation of wire arrays (wire diameters not to scale); open circle is the measuring wire--fixed for all measurements at 10.2 cm above ground plane.

4. A CODE FOR AN INFINITE WIRE ARRAY OVER A GROUND PLANE

A FORTRAN code was developed to implement various provisions of this development. Among its uses are the following.

1. In any parallel array of wires it must be ascertained whether a single-wire or a multiwire array code is required. This is determined by calculating the ratio

$$R_N = Z_{NN} I_N \Big/ \sum_M Z_{NM} I_M, \quad M = 1, 2, \ldots M' \tag{6}$$

   for all wires. For $R_N = 1$, there is no coupling between wire N and the rest of the array. The smaller this ratio becomes, the greater the degree of coupling. It remains to the user to select the point where the single-wire treatment is no longer valid (this judgment being based on overall system requirements). One caveat: the calculation is based on a good ground plane; for a lossy system, the level of wire interaction becomes larger as the wire array is positioned closer to the ground plane than is predicted by R_N. A more stringent requirement for R_N is required for an array near the earth than for an aerial array.

2. For special array configurations, where the wire impedances and end loads are similar, a circuit analysis can be performed on the array-equivalent single-conductor synthesis. An example of such an analysis appears in an Army Corps of Engineers study.[3]

3. The code outputs the relative current distribution among the wires for the infinite array case. While this fact has some intrinsic interest, caution must be exercised in interpreting these data since, for most cases of interest, wire-end loading plays a dominant role in determining wire signal levels.

The infinite parallel-wire array code outputs

1. all input data,

2. the level of wire interaction,

3. the relative current distribution among the array wires for the infinite transmission line,

---

[3]*EMP Disconnect and Protection for Commercial Power Feeders--Otis AFB Pave Paws Radar*, *U.S. Army Corps of Engineers*, *HNDSP-77-358-ED-SR (30 September 1977)*.

4. the impedance to ground for all array wires for the infinite transmission line, and

5. the impedance to ground of the wire array for the infinite transmission line.

The code input data are

NUM = number of wires,

RAD(N) = radius of wire N,

Y(N) = height of wire N above the ground plane, and

X(N) = horizontal location of wire N along the ground plane measured with respect to any arbitrary but fixed reference point. X(N) must be a positive value.

The code is designed to handle a maximum of 30 wires although this limit can be increased by altering the dimension statements.

Any consistent set of units may be used for all input data. A listing of the FORTRAN program follows. Near statement number 6 subroutine GELG is called; this is an IBM-supplied subroutine for the solution of a set of simultaneous linear equations.

```
      DIMENSION RAD(30), X(30), Y(30), Z(30,30), COEFL(900), COEFR(30)
      DIMENSION CUR(30), ZZ(30), ACUR(30)
      DIMENSION VOLT(30), ABC(30)
C
      NAMELIST/LISTA/NUM,RAD,X,Y
C
C  NUM IS THE TOTAL NUMBER OF CONDUCTORS
C
C  RAD IS THE RADII OF THE INDIVIDUAL WIRES
C
C  X(M), Y(M) ARE THE POSITION VECTORS OF THE WIRES MEASURED WITH
C  RESPECT TO THE GROUND PLANE AND WIRE 1
C
      READ(5,LISTA)
C
C
      WRITE(6,22)
   22 FORMAT(' MULTIPLE PARALLEL LINES ABOVE GROUND... VARIOUS PARM.')
      WRITE(6,23)
      WRITE(6,18)NUM
   18 FORMAT(10X,20HNUMBER OF WIRES ARE ,I2/)
      DO 24 N=1,NUM
      WRITE(6,19)N,RAD(N)
   19 FORMAT(10X,15HRADIUS OF WIRE ,I2,4H IS ,E10.4)
```

```
24    CONTINUE
      WRITE(6,23)
      DO 20 N=1,NUM
      WRITE(6,21)N,X(N),Y(N)
21    FORMAT(10X,5HWIRE ,I2,25H X AND Y COORDINATES ARE ,2F10.2)
20    CONTINUE
      WRITE(6,23)
23    FORMAT(' ')
      DO 4 M=1,NUM
      DO 4 K=1,NUM
      IF(K-M)16,17,16
16    Z(K,M)=60.*ALOG(((X(K)-X(M))**2+(Y(K)+Y(M))**2)**0.5/((X(K)-X(M))
     &**2+(Y(K)-Y(M))**2)**0.5)
      GO TO 4
17    Z(K,M)=60.*ALOG(2*Y(K)/RAD(K))
4     CONTINUE
      DO 5 M=1,NUM
      DO 5 K=1,NUM
      L=L+1
      COEFL(L)=Z(K,M)
5     CONTINUE
      L=0
      DO 6 K=1,NUM
      COEFR(K)=Y(K)
6     CONTINUE
      EPS=1.0E-07
      CALL GELG(COEFR,COEFL,NUM,1,EPS,IER)
      DO 7 N=1,NUM
      CUR(N)=COEFR(N)
7     CONTINUE
      DO 28 M=1,NUM
      DO 27 N=1,NUM
      VOLT(M)=Z(M,N)*CUR(N)+VOLT(M)
27    CONTINUE
28    CONTINUE
      DO 29 N=1,NUM
      ABC(N)=Z(N,N)*CUR(N)/VOLT(N)
      WRITE(6,30)N,ABC(N)
29    CONTINUE
30    FORMAT(10X,36HLEVEL OF ARRAY INTERACTION FOR WIRE ,I2,3H = ,E10.4)
      WRITE(6,23)
      CURR=CUR(1)
      DO 25 N=1,NUM
      IF(CURR-CUR(N))26,25,25
26    CURR=CUR(N)
25    CONTINUE
      DO 9 N=1,NUM
      ACUR(N)=CUR(N)/CURR
      WRITE(6,10)N,ACUR(N)
10    FORMAT(10X,20HCURRENT ON CONDUCTOR,I3,3H = ,E10.4)
9     CONTINUE
      WRITE(6,23)
      DO 11 N=1,NUM
      DO 12 M=1,NUM
      ZZ(N)=ZZ(N)+Z(N,M)*CUR(M)/CUR(N)
```

```
12    CONTINUE
      WRITE(6,13)N,ZZ(N)
13    FORMAT(10X,32HIMPEDANCE TO GROUND OF CONDUCTOR,I3,3H = ,E10.4)
11    CONTINUE
      WRITE(6,23)
      DO 14 N=1,NUM
      ZARR=ZARR+1./ZZ(N)
14    CONTINUE
      ZF=1./ZARR
      WRITE(6,15)ZF
15    FORMAT(10X,30HIMPEDANCE OF ARRAY TO GROUND= ,E10.4)
      STOP
      END
```

5. CONCLUSION

The wire array over a ground plan can be handled in a fashion analogous to the treatment given the shielded multiwire cable. A comparison of theory with experiment for a lossy ground plane shows a level of correlation comparable to that observed with the multiwire cables and adequate to justify the approach taken. It becomes a straightforward task to extend the present development to a code adequate to meet the full needs of an EMP vulnerability assessment and hardening program.

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